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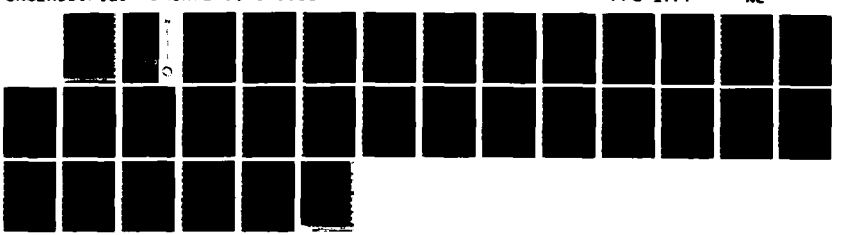

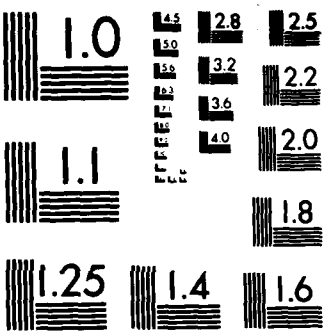

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ETL-0447

Development of electronic control of a superconducting gravity gradiometer — phase II

H. J. Paik

University of Maryland
Department of Physics and Astronomy
College Park, Maryland 20742

November 1986

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Prepared for
U.S. ARMY CORP OF ENGINEERS
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FORT BELVOIR, VIRGINIA 22060-5546

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During the contract period, we have completed the design and assembly of the breadboard feedback circuit for the new NASA superconducting gravity gradiometer. The circuit applies three kinds of feedbacks to the gradiometer instrument: (1) high frequency rejection, (2) cold camping, and (3) force rebalance. The primary purpose of these feedbacks is to increase the dynamic range of the instrument.

The circuit has been tested at room temperature and is awaiting a test in connection with the actual gradiometer.

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PREFACE

This document was generated under contract DACA72-85-C-0010 for the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, by the Department of Physics and Astronomy, University of Maryland, College Park, Maryland. It describes a continuation of the work done under contract DACA72-84-C-0004. (See reports ETL-0397, AD-A160-641, and ETL-0398, AD-A160-691.) The Contracting Officer's Technical Representative was Dr. Hans G. Baussus Von Luetzow.

The work described in this report is documented in three quarterly progress reports and a final report.

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BACKGROUND

A prototype superconducting gravity gradiometer has been demonstrated during the five-year period from 1980 to 1985 primarily with NASA support [1]. The instrument measured one diagonal component of the gravity gradient tensor. Without any feedback control, the passive superconducting gradiometer has yielded noise performance of 0.3 ~ 0.7 E $Hz^{-1/2}$ (I E ≡ 1 Eötvös ≡ $10^{-9} s^{-2}$).

We are now developing an advanced three-axis superconducting gravity gradiometer and a six-axis superconducting accelerometer under a joint sponsorship of NASA, Air Force Geophysical Laboratory and Army Engineers Topographic Laboratory. The primary objective of the new NASA contract is to develop a three-axis (three diagonal components) gravity gradiometer with 3 X 10^{-4} E $Hz^{-1/2}$ for spaceborne geodesy. The Air Force is funding specifically the development of the six-axis accelerometer [2], which measures three linear and three angular acceleration components. This instrument will be integrated with the gradiometer to provide dynamic signals for platform control and error compensation.

The Army Contract is to develop electronic control of the superconducting gravity gradiometer. The support came from the Army Corps of Engineers Topographic Laboratory (with Dr. H.G. Baussus von Luetzow as Contracting Officer's Representative) in two segments: $44,000 to cover Phase I effort (June 20, 1984 - April 19, 1985) and $51,000 for Phase II (October 4, 1985 - August 4, 1986). In Phase I, we studied the general problem of feedback

control of the gravity gradiometer and demonstrated the technique using room temperature accelerometers. In Phase II, we developed a breadboard circuit that applies three kinds of feedbacks to the cryogenic gradiometer. This report concerns the work performed under the Phase II Contract with the Army.

TECHNICAL REPORT

During the contract period: October 4, 1985 - August 4, 1986, we have completed the design and assembly of the breadboard feedback circuit for the new NASA superconducting gravity gradiometer. The circuit applies three kinds of feedbacks to the gradiometer instrument: (1) high frequency rejection, (2) cold damping, and (3) force rebalance. The primary purpose of these feedbacks is to increase the dynamic range of the instrument.

The test of the prototype gradiometer has shown that the dynamic range of the gradiometer can be exceeded due to resonant modes of the instrument and the cryostat insert driven by seismic noise. In the early work, this problem has been overcome by applying passive vibration isolation that attenuates the seismic noise above 1 Hz. In order to extend the sensitivity of the instrument by three orders of magnitude for space application, and/or to realize the demonstrated sensitivity ($\lesssim$1 E $Hz^{-1/2}$) in a moving base environment where background seismic noise can be four orders of magnitude higher than in the laboratory, it is essential that the dynamic range of the instrument is increased by at least four orders of magnitude by means of feedback. In Phase II of the Army Contract, we assembled the feedback circuit which can

accomplish this task.

(1) The high frequency spectrum of the gradiometer output (which is mainly seismic) above the signal bandwidth is fed back to the SQUID to reject the interfering seismic signals. (2) The signals around the two resonant modes of the coupled oscillator system in each axis of the gradiometer are narrowbanded, 90^{o} phase-shifted, and fed back to the gradiometer proof masses to actively damp the resonances. (3) Finally, the signals in the signal bandwidth (0 - 1 Hz) are fed back to the proof masses with 180^{o} phase shift to force-rebalance the gradiometer. The circuit has been tested at room temperature and is awaiting a test in connection with the actual gradiometer.

Six almost-identical circuit boards are needed to cover all the modes in the three-axis gradiometer. With the available funds in the Army Contract, we have completed only one of these boards. After tests and adjustments, five additional copies of this circuit will have to be assembled. We hope to receive Phase III funds to carry out this task.

Another type of electronic control needs to be applied to the gradiometer-accelerometer system. With twelve signal channels and hundreds of parameters to adjust in the combined system, it is essential that the instrument is computer-controlled. Software will have to be developed for automatic initialization, calibration, and platform control. As a first step in this direction, computer interface electronics for the two instruments have been constructed with funds from NASA and the Air Force. Much more work remains to be done in this area.

We attach here three quarterly progress reports that cover

the period of this contract. The detailed theoretical and experimental work on the superconducting gravity gradiometer has been reported to NASA (Reference 1).

REFERENCES

[1] Final Report on NASA Contract NAS8-33822, University of Maryland (June 1986).

[2] H.A. Chan, H.J. Paik, M.V. Moody and J.W. Parke, IEEE Trans. Mag., MAG-21, 411 (1985).

PROGRESS REPORT

DEVELOPMENT OF A THREE-AXIS SUPERCONDUCTING GRAVITY GRADIOMETER AND A SIX-AXIS SUPERCONDUCTING ACCELEROMETER

NASA Contract NAS8-33822
Army Contract DACA 72-84-C-0004
Air Force Contract F19628-85-K-0042

for the period of

November 1, 1985 to January 31, 1986

Principal Investigator: H.J. Paik

Department of Physics and Astronomy
University of Maryland, College Park, Maryland

NASA: THREE-AXIS GRAVITY GRADIOMETER

STATUS SUMMARY

1. The method used previously for winding the negative spring coils has been found to be unreliable. A new technique is being devised.
2. The remaining components for the three-axis gradiometer are nearly completed. Assembly can begin as soon as two negative spring coils can be fabricated.
3. The 15" dewar insert is being modified to accomodate the three-axis system.

ACTIVITIES AND RESULTS

1. Negative spring coils:

   The method used for winding the negative spring coils in a previous test involved winding the coils on a ceramic coil form. We recently discovered a crack in one of these forms which had caused an open circuit. Further tests revealed such cracking was not an unlikely occurance. A new method similar to that used for winding the pancake coils is being developed. In the first few coils, the wire was not completely bonded to the coil form.

2. Other components:

   The remaining components for the superconducting circuits of the gradiometer are nearly completed. A sufficient number of these components which include the pancake coils, the transformers, and the superconducting heat and magnetic switches have been produced and tested to permit assembly of the gradiometer to begin. As reported last quarter, the mechanical components are completed.

3. Dewar insert modification:

In order to adopt the 15" dewar insert for use with the three-axis gradiometer a number of modifications are necessary. The main modification is a complete rewiring of the insert. The prototype single-axis gradiometer required approximately 30 lead wires; whereas the three-axis gradiometer will require over 200 lead wires. The rewiring involves installing additional connectors and filters at the room temperature end of the insert and high vacuum feedthroughs at the low temperature end. We expect to complete these modifications by the end of February.

PLANS FOR NEXT PERIOD

1. Complete the negative spring coils.
2. Assemble the three-axis gradiometer.
3. Complete the dewar insert modification.

ARMY: ELECTRONIC CONTROL OF THE GRADIOMETER

STATUS SUMMARY

1. The design of the control and feedback electronics has been completed and assembly has begun.

ACTIVITIES AND RESULTS

1. Control and feedback electronics:

   The Physics Electronics Shop has completed the design of the control and feedback electronics. The design allows for either manual control or remote control by computer for all primary functions. Due to difficulty in obtaining some components and several minor design changes, the assembly has been delayed. The assembly should be completed by the end of February.

PLANS FOR NEXT PERIOD

1. Assemble and test the control and feedback electronics.

AIR FORCE: SIX-AXIS ACCELEROMETER

SUMMARY OF OBJECTIVES

To develop a highly sensitive six-axis superconducting accelerometer in which rigid body motions of a single proof mass will be monitored using superconducting circuits coupled to SQUIDs. Linear and angular acceleration vectors will be measured simultaneously.

STATUS SUMMARY

1. The electrical components are nearly completed.
2. The design of the control electronics has been completed.
3. Work has begun on the experimental dewar.
4. The cryostat insert is being machined.
5. Methods for manufacturing the six-axis shaker are being investigated.

ACTIVITIES AND RESULTS

1. Electrical components:

   The components required for the superconducting circuits of the six-axis accelerometer are nearly completed. These components include superconducting coils, transformers and heat switches.

2. Control electronics:

   The Physics Electronics Shop has completed the design of the control electronics for the six-axis accelerometer and six-axis shaker. The assembly of this unit will begin in February.

3. Experimental Dewar:

W.S. Goree Inc. has begun work on the 24" experimental dewar. This dewar will contain integral mu-metal and superconducting shields. Delivery of the dewar is scheduled for the middle of March.

4. Cryostat Insert:

The bulk of the parts for the 24" cryostat insert have been delivered. These parts must be inspected and the vacuum can must be leak tested before assembly can begin. Also, we are still awaiting delivery of the fiberglass support tubes.

5. Six-axis shaker:

The six-axis shaker has been redesigned. Methods for producing the three large titanium rings for the six-axis shaker are being investigated. At this time forging these rings appears to be an attractive alternative to machining the rings from plates. Also, a piezoelectric transducer and the housing for this transducer which contains a mechanical amplifier have been ordered and received. We will conduct tests on these units to see if they perform as expected.

PLANS FOR NEXT PERIOD

1. Complete all components and assemble the six-axis accelerometer.
2. Assemble and test the control electronics.
3. Assemble the cryostat insert.
4. Place the order for the six-axis shaker.

PERSONNEL CHANGES

None

TRAVEL

None

PUBLICATIONS AND REPORTS

None

PROGRESS REPORT

DEVELOPMENT OF A THREE-AXIS SUPERCONDUCTING GRAVITY GRADIOMETER AND A SIX-AXIS SUPERCONDUCTING ACCELEROMETER

NASA Contract NAS8-36165
Army Contract DACA 72-84-C-0004
Air Force Contract F19628-85-K-0042

for the period of

February 1, 1986 to April 30, 1986

Principal Investigator: H.J. Paik

Department of Physics and Astronomy
University of Maryland, College Park, Maryland

NASA: THREE-AXIS GRAVITY GRADIOMETER

STATUS SUMMARY

1. A successful technique for winding the negative spring coils has been determined.
2. The niobium wire used to wind the pancake coils has been discovered to be defective.
3. Assembly of the three-axis gravity gradiometer has begun.
4. Modification of the 15" dewar insert is proceeding.
5. The electronic interface and control system for the three-axis gradiometer is nearly completed.

ACTIVITIES AND RESULTS

1. Negative spring coils:

   After numerous refinements in the technique, three negative spring coils have been wound successfully. This number is sufficient to allow assembly of the first axis of the gradiometer. The remaining coils will be produced at a later date.

2. Pancake coils:

   The niobium wire used to produce the numerous pancake coils needed for the three-axis gradiometer has been discovered to have a very low critical current. Tests conducted in the last week of April indicate a critical current of 6 to 10 Amperes which is far below the usual value of 50 Amperes for high quality 0.003" nobium wire. This wire was obtained from California Fine Wire Co.; whereas, previously the wire had been obtained from Supercon which ceased production in 1984. Upon consistent urging from our research group, Supercon is again supplying 0.003" nobium wire. Further

tests of the California Fine Wire Co. wire are necessary to fully understand the problem.

3. Three-axis gradiometer:

The assembly of the three-axis gradiometer began in the third week of April. This assembly is taking place in parallel with the production of the final components for the superconducting circuitry. We have been planning to cool down and test the first axis of the gradiometer in mid May. If we need to rewind some of the pancake coils, this schedule is likely to be delayed.

4. 15" dewar insert:

Due to the difficulties in producing the negative spring coils, the modification of the 15" dewar insert has been delayed. These modifications are now underway and should be completed within several weeks.

5. Electronics development:

The physics electronics shop expects to complete the assembly and testing of the interface and control system for the three-axis gradiometer by the second week of May. However, after the completion of this system and a single-axis portion of the feedback electronics, all other electronics development must be halted due to insufficient funds. This work includes the remaining feedback electronics for the gradiometer, and the interface and control electronics for the six-axis accelerometer.

6. Meeting:

Prof. H.J. Paik and Dr. M.V. Moody attended a Gradiometer Study Team meeting at Marshall Space Flight Center on April 14, 15. The purpose of this meeting was to discuss the proposal for a flight test of the Gravity Gradiometer using the Space Shuttle.

ARMY: ELECTRONIC CONTROL OF THE GRADIOMETER

STATUS SUMMARY

1. Work on the feedback electronics is continuing.

ACTIVITIES AND RESULTS

1. Feedback electronics:

   One of six identical circuit boards in the feedback network for the three-axis gravity gradiometer has been wire wrapped. Testing of this board is underway. After the production of a second of these boards, which is sufficient for a single axis, further electronics development must be halted due to insufficient funds.

PLANS FOR NEXT PERIOD

1. Complete the assembly and begin testing of two feedback circuit boards.

AIR FORCE: SIX-AXIS ACCELEROMETER

SUMMARY OF OBJECTIVES

To develop a highly sensitive six-axis superconducting accelerometer in which rigid body motions of a single proof mass will be monitored using superconducting circuits coupled to SQUIDS. Linear and angular acceleration vectors will be measured simultaneously.

STATUS SUMMARY

1. The first proof mass has been corrected and a backup proof mass is nearly completed.
2. Work is continuing on the electrical components.
3. The delivery of the 24" dewar has been delayed.
4. The insert for the 24" dewar is being assembled.
5. Work on the interface and control electronics has been temporarily halted.
6. Tests on the mechanical amplifiers for the six-axis shaker have indicated that the original design is deficient.

ACTIVITIES AND RESULTS

1. Proof masses:

   A method was devised for correcting the machining error in the first proof mass. This work has been completed. A second proof mass which was begun after the error in the first proof mass was discovered is nearly completed.

2. Electrical components:

   Tests have been performed with LC resonant circuits coupled to superconducting transformers to achieve high gain. These transformers will be used to drive the ac bridge networks of the six-axis

accelerometer. The tests were inconclusive because of stray coupling. Approximately 60% of the pancake coils used for levitation and sensing have been wound. All other components are completed.

3. Experimental dewar:

The delivery of the 24" experimental dewar being manufactured by W.E. Goree has been delayed. The delay is due mainly to the loss of a primary subcontractor. Delivery is now expected by the end of May.

4. Cryostat insert:

The insert for the 24" dewar is being assembled. The vacuum can has been anodized and is ready to be coated with lead. Due to the large number of electrical leads (approximately 700) great care must be taken in the assembly to minimize the boil-off rate of the liquid helium. The insert should be completed next quarter.

5. Interface and control electronics:

The Physics Electronics Shop has completed the design of the interface and control electronics for the six-axis accelerometer. The assembly has been halted, however, due to insufficient funds. It may be necessary to transfer the assembly of this system from the electronics shop to the laboratory. This will, of course, reduce the rate of progress.

6. Six-axis shaker:

The mechanical amplifiers which are driven by stacks of piezoelectric crystals in the six-axis shaker have been tested. These amplifiers were designed to have a gain of 10. The tests, however, indicated a gain of only 1 improving to 4 after alterations. Further analysis and improvement of the design is necessary

before the shaker can be built.

PLANS FOR NEXT PERIOD

1. Complete all components and begin assembly of the six-axis accelerometer.
2. Complete the assembly of the cryostat insert.

PROPERTY AND EQUIPMENT

1. Components of multichannel phase sensitive detector.
2. Components of shaker transducer.
3. Components of accelerometer.
4. Components of 24" cryostat insert.

PERSONNEL CHANGES

None

TRAVEL

Prof. H.J. Paik and Dr. M.V. Moody attended the Fourteenth Gravity Gradiometer Conference at Colorado Springs on February 11, 12 at which both gave presentations. The quarterly progress review was held at this location on February 10.

PUBLICATIONS AND REPORTS

None

PROGRESS REPORT

DEVELOPMENT OF A THREE-AXIS SUPERCONDUCTING GRAVITY GRADIOMETER AND A SIX-AXIS SUPERCONDUCTING ACCELEROMETER

NASA Contract NAS8-36165
Army Contract DACA 72-84-C-0004
Air Force Contract F19628-85-K-0042

for the period of

May 1, 1986 to July 31, 1986

Principal Investigator: H.J. Paik

Department of Physics and Astronomy
University of Maryland, College Park, Maryland

NASA: THREE-AXIS GRAVITY GRADIOMETER

STATUS SUMMARY

1. Problems with the Nb wire used for winding the pancake coils have been resolved.
2. The 15" dewar insert has been modified and tested.
3. A single-axis of the three-axis gravity gradiometer has been assembled and cooled.
4. The interface and control electronics for the three-axis gravity gradiometer has been completed and tested.
5. The technique for making high quality superconducting joints has been improved.

ACTIVITIES AND RESULTS

1. Pancake coils:

   Tests have shown that the Nb wire obtained from California Fine Wire Co. is of poor quality and is unsatisfactory for use in the gradiometer. Tests have also shown that the Nb wire obtained from Supercon is of good quality; however, the insulation applied by Supercon is not of acceptable quality. Consequently, bare Nb wire is now being obtained from Supercon, and this wire is then shipped to California Fine Wire Co. where it is coated with insulation.

2. 15" dewar insert:

   The 15" dewar insert has been modified to test the new gradiometer. Tests have shown that, even though the number of electrical leads has been substantially increased, the He boil off rate is still low enough to allow a week between the transfers.

3. Three-axis gravity gradiometer:

The assembly of a single-axis section of the three-axis gradiometer has been completed and cooled to 4.2 K. During this initial cool down, a major design problem was discovered. The problem concerned the heat switches used for storing persistent currents in the superconducting loops of the gradiometer. The Nb leads between these switches and the superconducting joints were not sufficiently well heat sunk. Consequently, when the heat switches were activated at high current levels, the temperature of the joints was too high for the joints to function. Furthermore, due to the high power dissipation levels during joint failure, damage was done to the superconducting circuits.

At this point the gradiometer has been warmed to room temperature and inspected. Most of the damage appears to be in accessible areas. We are attempting to repair this damage without disassembling the gradiometer. A second cool down is planned in August.

Concurrently, the parts for the second and third axis are being completed. The coil form holders have been redesigned to facilitate repairs.

4. Interface and control electronics:

The physics electronics shop has completed the interface and control electronics for the three-axis gravity gradiometer. This system was tested during the cool down of the first axis of the gradiometer at which time several problems were discovered. These problems include improper circuit grounds, 60 Hz interference, and turn on transients in the power supplies. The electronics shop is in the process of improving the circuitry to eliminate these problems.

5. Superconducting joints:

Though tests had shown that the spot welded superconducting joints were of high quality with critical currents on the order of 15 to 25 amperes at 4.2 K, the technique for making these joints was very critical. Consequently, tests were conducted on joints made by spot welding the superconducting wires to foil. Though the number of spot welds increased by a factor of two, the precision required for each joint was substantially reduced. Furthermore, the critical currents of all joints tested was greater than 25 A.

6. Software development:

Since the interface and feedback electronics for the three-axis gradiometer are computer controlled, software is required to operate these systems and to test the gradiometer. This software is being developed in conjunction with the test of the first axis of the gradiometer.

7. Meetings:

Drs. H.J. Paik and M.V. Moody attended the American Geophysical Union meeting on May 22 at Baltimore where they presented papers.

8. Personnel changes:

Mr. Young Soo Kang, a mechanical engineer, joined the group on July 15, 1986. He will be working for both the NASA and Air Force projects.

PLANS FOR NEXT PERIOD

1. Complete the repairs on the first axis of the gradiometer and continue testing.
2. Complete the parts for and begin assembly of the second axis.

3. Test the improved interface and control electronics.

4. Continue software development.

ARMY: ELECTRONIC CONTROL OF THE GRADIOMETER

STATUS SUMMARY

1. One feedback circuit board has been completed and is ready for testing.

ACTIVITIES AND RESULTS

1. Feedback electronics

   The assembly and preliminary tests of one of six identical feedback circuit boards has been completed. Further testing must wait until a working gradiometer is available.

PLANS FOR NEXT PERIOD

1. Test the feedback electronics if circumstances permit.

AIR FORCE: SIX-AXIS ACCELEROMETER

SUMMARY OF OBJECTIVES

To develop a highly sensitive six-axis superconducting accelerometer in which rigid body motions of a single proof mass will be monitored using superconducting circuits coupled to SQUIDs. Linear and angular acceleration vectors will be measured simultaneously.

STATUS SUMMARY

1. The second proof mass has been completed.
2. The levitation and sensing coils are being rewound.
3. The 24" dewar has been delivered.
4. Work is continuing on the 24" dewar insert.
5. Work on the interface and control electronics has been restarted.

ACTIVITIES AND RESULTS

1. Proof mass:

   The machining of the second proof mass has been completed. The surfaces of this proof mass have been polished optically flat in an effort to obtain a high electrical quality factor. The three planes of the proof mass are orthogonal to 1 part in 10^4.

2. Levitation and sensing coils:

   Due to problems with the quality of the Nb wire obtained from California Fine Wire Co., the levitation and sensing coils are being rewound with wire manufactured by Supercon. The 24 livitation coils are completed. The rewinding of the 24 sensing coils is still in progress.

3. Experimental dewar:

   The 24" experimental dewar was delivered at the end of May. This

dewar will be tested at the earliest convenience.

4. Cryostat insert:

   Assembly of the 24" dewar insert is progressing. The vacuum can is being coated with lead to provide a superconducting shield against electromagnetic interference. After this evaporation the insert must then be wired for the six-axis accelerometer.

5. Interface and control electronics:

   Work on the interface and control electronics has been restarted using personnel from within the laboratory. This arrangement should substantially reduce the assembly cost. Also an instrument consisting primarily of 10 lockin-amplifier boards has been assembled. This instrument will be used to demodulate the signals from the six-axis accelerometer.

PLANS FOR NEXT PERIOD

1. Complete all components and begin assembly of six-axis accelerometer.
2. Continue assembly of dewar insert.
3. Continue assembly of interface and control electronics.

PROPERTY AND EQUIPMENT

1. Zenith Z-100 computer system with 5 MB fixed disk (transferred from AFGL).
2. Okidata microline 83A printer (transferred from AFGL).

PERSONNEL CHANGES

Mr. Young Soo Kang, a mechanical engineer, joined the group on July 15, 1986. He will be working for both the NASA and Air Force projects.

TRAVEL

At the 11th International Conference on General Relativity and Gravitation held at Stockholm on July 7-12, Dr. Paik chaired a session on the terrestrial experiments and presented a paper on the inverse square law experiment. His travel was sponsored by the conference and NSF.

END

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